
Navy Mimics
hAgfISh

# SLIME to Support the WARFIGHTER

## Eel-like Creature Inspires Naval Surface Warfare Center Researchers to Innovate

Inspired by the defense mechanism of the Pacific hagfish, scientists from the Naval Surface Warfare Center Panama City Division (NSWC PCD) have produced a synthetic version of hagfish slime to support Navy warfighters.

Slithering along the bottom of the ocean, a long, flat fish navigates the sea floor. Resembling an eel with its long grey body and paddle-like tail, it moves smoothly and fluidly, examining a sunken lure placed there by researchers. As the sinuous fish explores its find, a kitefin shark lurks nearby, circling the smaller animal intently. The shark approaches its prey, hovering within striking distance and suddenly lunges out, grasping its victim in its jaws. Almost instantaneously, a murky cloud engulfs the shark's mouth, causing the predator to wretch and release its target. The shark swims off, discouraged, leaving its prospective dinner relatively unscathed.

The nearly preyed-upon animal is the hagfish, and it just introduced the shark to its exceedingly effective defense mechanism. The hagfish deters would-be predators by releasing a secretion that forms a thick slime—clogging the mouth and gills of the attacker. This allows the hagfish to escape as the attacker chokes and retreats. While scientists have known of this capability for decades, they've only recently begun to document and observe the capabilities of the hagfish with video recordings and tests.

With these data, researchers have gained insights on the hagfish, its slime, and future practical applications for science, medicine and/or military functions. In particular, the Navy is exploring ways in which the properties of hagfish slime could benefit Sailors, Marines and naval platforms on land and at sea.

## UGLY, SPINELESS & FORMIDABLE

The hagfish (scientific name *Myxini*) is a spineless, jawless, virtually blind fish that resides along the sea floor. Despite the lack of actual vertebrae, it does technically have a spine made of cartilage. Occasionally called "slime eels" and frequently referred to as one of the ugliest fish on the planet, the hagfish inhabits cold waters all over the globe, and can live as deep as 5,500 feet. While it resembles an eel in appearance, it actually belongs to the class *Agnatha*, which encompasses fish that lack jaws.

With 76 different species of hagfish, the appearance and size can vary, although hagfish tend to grow to a length of 16 to 40 inches (40 to 100 centimeters (cm)). The color of each fish depends on its species and location, with observed colors including shades of grey, brown, pink, red, blue and white. Some hagfish can be spotted or mottled in their coloring, and past observations indicate that its coloring may be determined by the color of the surrounding sea floor.

The hagfish typically consumes the carcasses of other marine animals for food, providing a crucial service to the ecosystem by essentially cleaning dead creatures from the sea floor. That said, its feeding habits can be unsettling to casual observers. A hagfish will essentially tear a hole into the dead animal—often tying its own body into a knot to gain additional leverage and generate force in biting—and then proceed to bury themselves in the hole, tunneling inside the animal and consuming it from the inside out. After eating, it can go for months until its next meal. Its slow metabolism and ability to absorb nutrients through its skin and gills appear to enable this substantial time between feedings.

Due to its loose skin, a hagfish is capable of sliding through tight spaces, even able to slip through a gap half its body width. The skin is connected to the fish's body in a line down the center of its back and provides

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flexibility for navigating narrow passageways and evading predators. It is possible for a predator to puncture the skin of a hagfish without stabbing into the muscle underneath, providing the hagfish an opportunity to free itself with its unique defense mechanism.

## SLIME TIME

The hagfish has proven adept at evading larger predators such as marine mammals, sharks and cephalopods (octopus, squid). In less than a second, a stressed hagfish can emit a coiled thread—known as a skein—which contains mucins and fine fibers. Once ejected, the skein rapidly expands when mixed with seawater. According to research conducted by Dr. Douglas Fudge and his colleagues at the University of British Columbia's Department of Zoology, the completed slime is comprised of 99.996 percent seawater, with the remaining components being the mucins (0.0015 percent) and fiber threads (0.002 percent). It's considered to be 1,000 times more dilute than other known animal mucus secretions. Once the skeins are introduced into seawater, the material expands approximately 10,000 times in a matter of milliseconds.

## The Basics About the hAgfISh

Hagfish are eel-shaped, slime-producing marine fish. They are the only known living animals possessing a skull but no vertebral column, although they possess a rudimentary spine composed of cartilage. Similar to lampreys, hagfish are jawless. Today's hagfish remains similar to hagfish from over 300 million years ago.

**Class:** *Agnatha*

**Family:** *Myxindae* (all oceans); *Eptatretidae* (all oceans except the Northern Atlantic)

**Clutch Size:** 1 to 30 (dependent on species)

**Length:** 16 to 40 inches (40 to 100 cm)

**Species:**
Pacific hagfish (*Eptatretus stoutii*)
Black hagfish (*Eptatretus deani*)
Gulf hagfish (*Eptatretus springeri*)
Inshore hagfish (*Eptatretus burgeri*)
New Zealand hagfish (*Eptatretus cirrhatus*)
Patagonian hagfish (*Myxine affinis*)
Cape hagfish (*Myxine capensis*)

**Fun Fact:** Hagfish Day, founded in 2009, is celebrated on the third Wednesday in October.

Demonstrating the elasticity of the authentic Pacific hagfish slime.
*Ron Newsome*

The hagfish is the only known animal that creates slime by emitting skeins. Whereas other animals with similar defense mechanisms store liquid slime internally prior to discharge, the hagfish relies on the presence of seawater mixing with the skein filaments to choke and deter predators. The mucin-fiber thread substance only accounts for approximately three to four percent of the fish's body mass.

To discharge the material, the hagfish has 90 to 200 slime pores running along each side of its body. When attacked, the animal has the capability to eject slime through a selective grouping of pores which are closest to the predator, or specifically within the attacker's mouth.

Once the slime is dispelled, the predator's mouth and gills become obstructed and it flees. Rather than binding or halting water entirely, the substance slows water dramatically, acting like a sieve that prevents efficient breathing. This is known as viscous entrainment. Ironically, the hagfish can actually choke on its own slime occasionally, but it has two strategies available to counteract that possibility. If necessary, it can tie its own body into a knot (much like it does when it feeds) and run the knot up along its body to wring the material off itself. Additionally, the hagfish can "sneeze" to clear its breathing path.

Dr. Josh Kogot displays a sample of synthetic hagfish slime recreated from alpha and gamma proteins of the Pacific hagfish.
*Ron Newsome*

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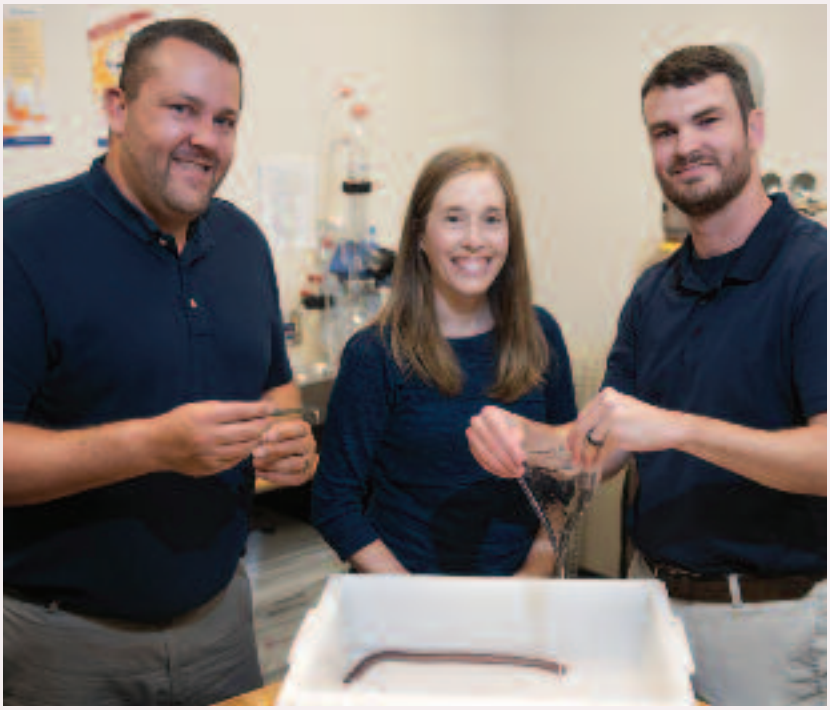

NSWC PCD scientist and engineers, Dr. Josh Kogot, Dr. Michelle Kincer and Dr. Ryan Kincer, compare synthetic hagfish slime (left) and authentic Pacific hagfish slime (right).

*Ron Newsome*

## INITIAL RESEARCH

In 2014, NSWC PCD personnel founded the Biotechnology Interest Group (BIG), spearheaded by biochemist Dr. Josh Kogot of the Intelligent Sensing and Irregular Warfare Branch. The group's goal is to provide the Navy with innovative biotechnology and bio-inspired solutions to complex technical challenges with consistency and quality by way of focused research and development efforts.

Every month, BIG assembles a small group of subject matter experts to discuss current research and discuss possible bio-inspired and biomimetic topics to explore. In early 2015, Mr. Rudy Arrieta—a colleague of Dr. Kogot's and a chemistry specialist—mentioned a video he had seen on the defense mechanisms of the hagfish. After brainstorming a number of possible naval applications, the group ultimately decided to pursue an Innovation Cell (iCell) project to perform fundamental applied research with hagfish slime for naval applications.

Along with Dr. Kogot, the core research group includes Dr. Ryan Kincer (materials engineer), Dr. Michelle Kincer (materials engineer) and Mr. Preston Postl (microbiologist). Narrowing the field from the aforementioned variety of hagfish species, the team began examining the Pacific hagfish (*Eptatretus stoutii*), exploring the capability of the slime to rapidly expand. Initial research focused on the natural slime created by the hagfish, and was funded by the iCell and Navy Innovative Science and Engineering (NISE) division. Recognizing the unique characteristics and fast-acting capabilities of hagfish slime, NSWC PCD personnel saw value in harnessing its properties.

## The SponSoRS

**Naval Innovative Science and Engineering**

The NISE program was founded in 2009, and funds efforts in basic and applied research, technology transition, workforce development and capital equipment investment. Since the program was established, it has supported numerous projects with a focus on Science, Technology, Engineering and Mathematics (STEM). NISE provides additional opportunities for these technical fields, to include continuing education, rotational assignments and certifications, and enables the Navy to invest in aging infrastructures and equipment. Technical collaboration also serves as a key facet of the program, allowing warfare centers the opportunity to function in a collaborative manner and interact with other industry and academic experts.

**Office of Naval Research**

ONR is a pioneer in the public support of science and technology research that benefits both the naval services and the nation. Founded in 1946, ONR invested in some of the earliest computers, spearheaded research into deep sea exploration and supported countless other groundbreaking innovations throughout the years. The office maintains an organizational strategy that enables investment in technology focus areas that will support future operational concepts, intending to equip Sailors and Marines with tools to operate effectively and safely.

For more information about ONR, visit www.onr.navy.mil.

Dr. Ryan Kincer marvels at the hagfish's distinctive mechanism.

"The hagfish is the only known animal that secretes fully formed intermediate filaments. While the hagfish filaments are often compared to spider silk, the spider spins silk from a liquid precursor," he says. "Since the hagfish filament is preformed inside specialized cells along the body, the release of the filaments and mucin causes the slime to be formed instantaneously. This instantaneous expansion was another unique material property that intrigued us as other super absorbing materials usually take minutes to fully hydrate."

Following the initial study on the naturally-produced material, the research team began to explore ways in which hagfish slime could be synthetically reproduced for Navy use. After roughly six months of research, the scientists introduced alpha and gamma proteins drawn from the Pacific hagfish to the Escherichia coli bacteria—commonly known as E.coli. Alpha proteins are a key plasma or blood protein that binds to copper, nickel, fatty acids and other materials; and gamma proteins fall under a class of spherical, globe-like proteins which respond to antigen stimulation by forming into the common form of immunoglobins (i.e. antibodies). The proteins were retrieved from the bacteria and run

*Ron Newsome*

A hagfish protruding from a sponge.
*www.flickr.com/noaaphotolib*

We have had a number of successes early in our research, which has opened our imagination to many more hypotheses and potential future applications.
—Dr. Josh Kogot

through a series of isolation and purification processes. Following those steps, the proteins would ultimately be combined together, swiftly joined into a crosslinked solution via centrifuge.

This solution was compared to the naturally-occurring hagfish threads via a scanning electron microscope, confirming synthetic reproduction of the material. While this was a significant achievement, the scientists conducting these studies note that there is still a lot of work to be done.

"This is an ongoing research effort that is still in its infancy—only 12 to 18 months of active research at our laboratory," says Dr. Kogot. "We have had a number of successes early in our research, which has opened our imagination to many more hypotheses and potential future applications."

The work performed on generating the synthetic slime, as well as ongoing research and development efforts, has been funded by the Office of Naval Research (ONR).

## USING THE SLIME

Having successfully created a synthetic version of the slime, NSWC PCD scientists continue to examine ways in which the material can be

## A Scientist's Perspective: Why Go Navy?

Dr. Kogot, Dr. Kincer and their NSWC PCD colleagues represent a few of the many skilled and knowledgeable science and technology professionals in the Navy. Although there are abundant opportunities for scientists of their pedigree in the public sector, the Navy and the Department of Defense (DoD) continue to draw upon some of the best researchers on the planet.

Before joining the staff in Panama City, Dr. Kogot spent five years at the Army Research Laboratory, focusing on basic and applied research. While there, he utilized his background in biochemistry to perform biomimicry and bio-mimicry research to develop new sensing technologies with peptides, created new protein engineering strategies and crafted novel biomaterials for biosensing, bioelectronics and biophotonics.

"I excelled at transitioning and translating research in the university laboratories to DoD-relevant technologies," said Dr. Kogot. "My goal upon arriving to NSWC PCD was to continue to transition promising basic research in biotechnology to mature the capability towards a field-able product."

Recognizing that biotechnology has great potential to provide military personnel with a decisive battlefield advantage, he focused on providing low-cost, lightweight and robust solutions.

"My affinity for working for the Navy and DoD is to protect the warfighter and give them the advantage to return home safely," continued Dr. Kogot. "There are a number of people in my family that served or are serving in the military. I believe that using my skills and expertise to protect my family members and fellow citizens is an honorable commitment."

Dr. Ryan Kincer also identifies his work with the Navy as being particularly rewarding.

"As a research scientist, I've always had a profound interest in the newest technology and latest revolutionary materials," he says. "Being a researcher for the Navy allows me to apply my passion for science to help keep our warfighters equipped with the most advanced gear. I feel a sense of patriotism knowing that the materials we are developing in the laboratory may one day help on the battlefield."

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**—Dr. Ryan Kincer**

Dr. Ryan Kincer believes these science breakthroughs are integral in solving naval and defense-oriented challenges. By contributing to these solutions, he finds considerable satisfaction in supporting the military.

mass-produced while seeking to identify potential uses to the Navy. While development is early and new possible utilizations are frequently popping up, the team at NSWC PCD has a number of uses in mind.

"The potential applications that we envision are ballistics protection, firefighting, anti-fouling properties, diver protection and anti-shark spray," says Dr. Kogot. "Our intended use is for non-lethal and non-kinetic defense to protect the warfighter."

In terms of ballistics protection, the Navy could pursue the hypothesis posed by Dr. Fudge—now with Chapman University—that hagfish filament could serve as a renewable source capable of replacing synthetic, petroleum-based materials. With petroleum being a key component in Kevlar, a material commonly used in military combat helmets and ballistic vests, there is potential for synthetically-produced hagfish slime to be used in the development of innovative protective equipment.

Firefighting applications may be feasible based on the slime's ability to absorb and retain water. Synthetic slime with the same properties might be useful as a fire suppressant. Dr. Kincer notes that chemicals currently used for fire suppression frequently pose health and environmental concerns. The development of a slime-based extinguishing system offers the possibility of an effective, environmentally-friendly alternative. Additionally, similar to ballistics protection, advancing the understanding and application of this research could lend to the development of flame-resistant firefighting gear including suits and helmets.

Due to the slick nature of the slime, it may also hold promise for anti-fouling technology on Navy ships. Anti-fouling refers to materials and coatings used to prevent biofouling, the buildup of microorganisms, animals and vegetation on wet surfaces. The accumulation of barnacles, seaweed, mollusks and other stowaways on a hull can add weight and increase drag, which can result in up to a 10 percent speed reduction. Biofouling can also impact fuel efficiency and potentially increase greenhouse gas emissions. Beyond the operational impacts, some anti-fouling materials can be harmful to the environment in terms of water pollution and impacts to marine life.

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A synthetic coating derived from the slime could provide an eco-friendly substitute.

Dr. Kogot also mentioned diver protection and anti-shark spray—allowing Navy personnel to use synthetic slime much in the same way that the hagfish would. The NSWC PCD scientists and researchers posit that individuals could be equipped with technology that could dispense the manufactured filaments, mixing with seawater to produce a protective slime to deter sharks, cephalopods or any other marine life that might pose a threat.


Pacific hagfish.
*Linda Snook*

The unique qualities of hagfish slime could make it a true game-changer in marine technology. Dr. Kincer points out that the composition of the material is an advantage for the Navy, reiterating that the slime is made of over 99 percent seawater (and seawater is of course abundantly available to Sailors at sea). This would allow for the systems delivering the slime to remain compact and manageable—even a small amount of the source material could create large quantities of slime in mere seconds, delivering a powerful punch for its intended purposes.

In addition to the future capabilities mentioned here, the research team continues to investigate potential delivery systems, ways in which they can increase the slime's ability to attach to different surfaces and methods to ensure its effectiveness in a variety of environments.

## THE NAVY & BIOMIMETICS

Hagfish slime is far from the first instance of animals inspiring marine technologies and human solutions.

Sonar is one of the most noteworthy instances of a biomimetic technology used by the Navy. Improved understanding of and insight on marine mammals, including whales and

## What is biomimicry?

Biomimicry (or biomimetics) is a methodology pertaining to technology and infrastructure development that supports sustainable solutions to challenges by emulating nature's patterns and strategies. Whether innovation is spurred by an observed process in nature and translated to a human technology or approach, or an innovator identifies an existing shortcoming and turns to nature for inspiration, biomimicry connects the fields of biology and engineering.

Famous examples of biomimicry are abundant in everyday life. Velcro, for example, was developed by Swiss scientist George de Mestral, who crafted the material after observing how burrs latched onto his dog's fur. Looking closer, he noted the tiny hooks at the end of burr's prongs, which inspired de Mestral to develop hooked material opposite tiny looped weaves to create this adhesive material. Japanese engineers have looked to the beak of the Kingfisher bird to design a more streamlined high-speed train, which increases speed, reduces fuel energy requirements and eliminates shock waves in tunnels previously created by the trains' more blunted nose. In additional these examples, a number of novel cooling systems, solar technologies, prosthetics and camouflage applications have all drawn their inspiration from animals and biological processes.

For more information on biomimetics and the ways in which humans benefit from nature's efficiencies, visit https://biomimicry.org.

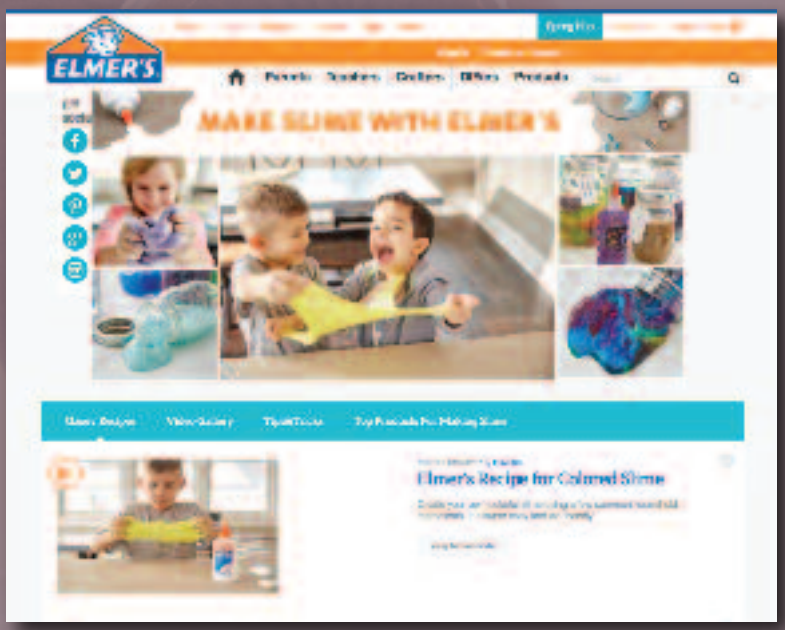
dolphins, as well as bats, and even cicadas has helped naval researchers build upon sonar systems that previously evolved in nature. Additionally, the efforts have aided in improving understanding of marine life, expanding the knowledge of how these animals are affected by Navy activities as well as how those effects can be mitigated.

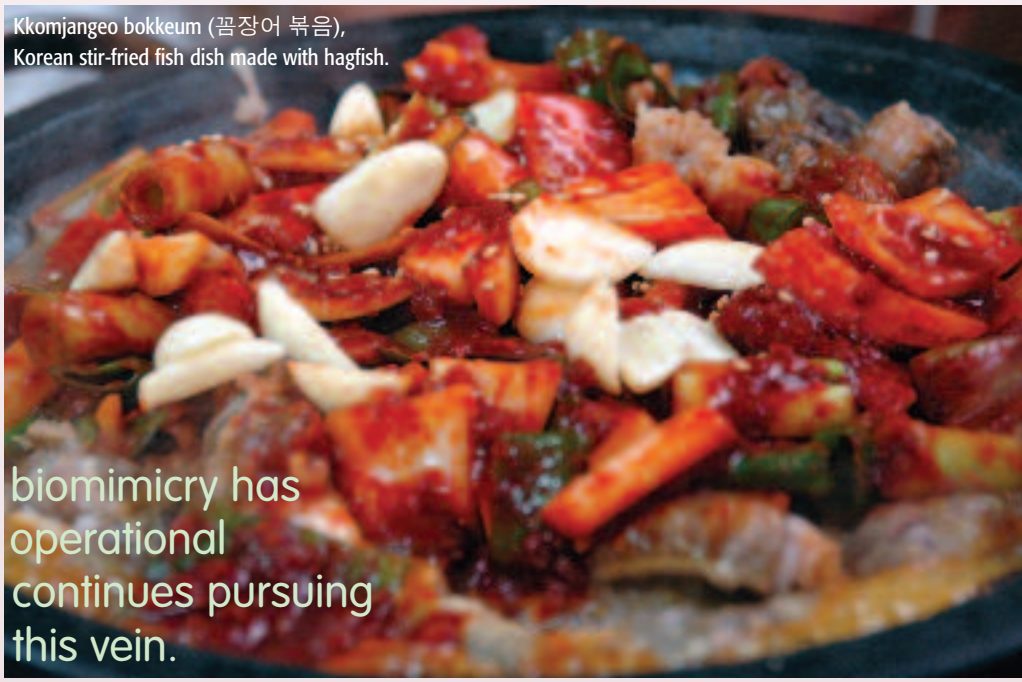
In recent years, ONR has also recognized unique attributes of sharks, inspiring their laboratories to mimic shark skin. Shark skin is covered with flexible layers of small teeth—known as dermal denticles—which create a low-pressure zone that propels the shark forward and reduces drag. The denticles also prevent microorganisms from attaching to the predators. These realizations prompted ONR to develop a material known as Sharklet which prevents biofouling and reduces drag for ships and submarines.

Autonomous underwater vehicles (AUV) have also benefited from nature's sleek designs, with the Naval Research Laboratory taking a cue from the bird wrasse fish. One particular AUV—known as the Wrasse-inspired Agile Near-shore Deformable-fin Automaton (WANDA)—was equipped with a pectoral fin, similar to its namesake, which allows it to operate in littoral zones that require low speeds and high maneuverability.

## Make Your Own Slime

To make your own colored, glittered or jumbo size slime, mix 1/2 tablespoon (tbsp.) of baking soda, 1 tbsp. of contact lens solution, 4 fluid ounces of Elmer's White school glue, and your choice of food coloring or visit elmers.com/Slime.





Kkomjangeo bokkeum (꼼장어 볶음), Korean stir-fried fish dish made with hagfish.

Each of these instances of biomimicry has provided tactical and operational advantages, and the Navy continues pursuing new opportunities in this vein.

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"We are continually looking to expand the bio-inspired and biomimetic research as part of the mission and ongoing research of the biotechnology group," explains Dr. Kogot. "One of my ongoing basic research projects involves recreating the electro-sensing capability of sharks, skates and rays using microfluidics, material science and electrochemistry. Sharks, skates and rays have a highly-developed electrosensing capability through a series of canals and pores on the animal body called the Ampullae de Lorenzini. Using different canal lengths and canal diameters, the animal can sense long-range electric field changes or sense small perturbations in electric field at short-range. Most of these capabilities are intended for use in prey detection or environmental sensing."

Dr. Kogot also references ongoing and forthcoming projects pertaining to biodegradable, three-dimensionally printed materials, whole-cell sensors and bioelectronics. "Our cross-disciplinary research team of biochemists, chemists, material engineers, microbiologists and electrical engineers positions us well to do cutting-edge, biotechnology research," he said.

## CONCLUSION

The hagfish proves often that it is not an easy meal for predators, and its resilience offers the Navy a great deal to think about in terms of defense and operational best practices. Having achieved an extraordinary breakthrough in manufacturing the synthetic slime, NSWC PCD scientists continue to delve into the pragmatic capabilities of this unique material. From body armor and firefighting, to anti-fouling and shark repellant, the possibilities hold great promise for the Navy and its researchers. ⚓

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### The Basics About the Naval Surface Warfare Center Panama City Division

NSWC PCD is one of ten Navy warfare center enterprises located throughout the United States. These centers supply the technical operations, people, technology, engineering services and products needed to equip and support the Fleet and meet the warfighters' needs. Serving as the Department of the Navy's principal research, development, test and evaluation assessment activities for surface ship and submarine systems and subsystems, NSWCs support offensive and defensive systems associated with surface warfare and related areas of joint, homeland and national defense systems from the sea.


The mission of NSWC PCD is to conduct research, development, test and evaluation, in-service support of mine warfare systems, mines, naval special warfare systems, diving and life support systems, amphibious/expeditionary maneuver warfare systems and other systems that occur primarily in coastal regions and to execute other responsibilities as assigned by Commander, Naval Surface Warfare Center. It exists to understand the technical dimensions of warfighter requirements, to collaborate with industry, academia and other warfare centers, to develop solutions and to certify that safe and effective solutions are achieved.

For more information on NSWC PCD, visit www.navsea.navy.mil/Home/Warfare-Centers/NSWC-Panama-City.